ART. IV.—*On the Chemical Composition of Amphibole;* by S. L. PENFIELD and F. C. STANLEY.*

OWING to the common occurrence of amphibole and the important rôle it plays as a rock-making mineral, its chemical composition has naturally been the subject of repeated investigation, with the result that there has accumulated a large amount of analytical data, yet there is still wanting a satisfactory explanation of the variations in chemical composition exhibited by the mineral. The present investigation was undertaken, therefore, with the hope that by having a few analyses made with the utmost possible care on material of unquestionable purity a clue might be gained which would help to elucidate some of the difficulties presented by the problem. And here at the outset it may be stated that the present communication is only a preliminary one: It is intended to make more analyses than are given in this paper, but since it happens that the work must be interrupted for a time, it is believed that data of sufficient interest have already been accumulated to warrant publication. It is also intended to make a careful study of the optical properties of the various amphiboles which have been analyzed, but the carrying out of that part of the investigation must be left for the future.

Turning to text-books and treatises on Mineralogy for an explanation of the chemical composition of amphibole, it is found that the formulas suggested by Tschermak† are the ones which are almost always given. Briefly stated, Tschermak's

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* NOTE:—Prof. Penfield had had the problem of the chemical composition of amphibole in mind for a number of years, but the opportunity for carrying out an investigation to solve it did not present itself until about two years ago, when Mr. F. C. Stanley, a graduate student, commenced, under his direction. the series of amphibole analyses which are quoted in the present paper. These analyses formed the basis of a thesis which Mr. Stanley presented in 1905 for the degree of Doctor of Philosophy. The results of the analyses were not published at that time, for it was hoped, as Prof. Penfield states, that the investigation could be continued and made more complete, but circumstances prevented Dr. Stanley from continuing the work, and hence during May and June, 1906, Prof. Penfield wrote up the investigation as far as it had proceeded. After his death in August last, the manuscript of the article presented here was found in his desk. Fortunately it was in such an advanced stage that it has been possible to print it almost exactly as Prof. Penfield left it, the only changes being occasional verbal ones and the only addition being the concluding paragraph, headed Summary and Conclusion.

Prof. Penfield, had he lived, would undoubtedly have extended the article somewhat by the discussion of still other analyses taken from the literature, and would, as was his invariable custom, have subjected the whole manuscript to rigorous revision. But as it stands it forms a clear, well developed and illuminating contribution, not only to the problem of the chemical composition of amphibole itself, but also to the wider problem of the composition of pneumatolitic minerals in general.—W. E. FORD.

† Mineralogische Mittheilungen, 1871, page 41.

theory is as follow: To tremolite, the simplest form of amphibole, the formula $CaMg_3Si_4O_{12}$ is assigned; ordinary green amphibole, actinolite, corresponds to $Ca(Mg,Fe)_3Si_4O_{12}$; while in varieties containing considerable amounts of sesquioxides, there is assumed the existence of an alumo-silicate molecule $(Ca,Mg)_2Al_4Si_2O_{12}$ and a corresponding one containing ferric iron, $(Ca,Mg)_2Fe_4Si_2O_{12}$. The last two molecules have only a theoretical existence; they are supposed to be isomorphous with $Ca(Mg,Fe)_3Si_4O_{12}$, but no pure chemical combinations corresponding to them have ever been observed. The presence of alkalies is ascribed to the existence of the metasilicate molecules $Na_2Al_2Si_4O_{12}$ and $K_2Al_2Si_4O_{12}$, the former being analogous to jadeite, $NaAlSi_2O_6$. Water is supposed to be due to alteration and there is no provision in the formulas for fluorine, which is an almost unfailing constituent of amphibole. In Tschermak's latest publication* the formulas suggested for amphibole are $CaMg_3Si_4O_{12}$, $CaFe_3Si_4O_{12}$, and two alumo-silicates, $CaMg_2Al_2Si_3O_{12}$ and $Na_2Al_2Si_4O_{12}$.

It is true that by a combination of the several molecules suggested by Tschermak theoretical compositions may be calculated which correspond rather closely to some of the analyses, but the formulas are in general found to be wanting in many respects when subjected to careful comparison with existing analyses, and Tschermak freely admits that the problem is one presenting numerous difficulties.

Rammelsberg† has pointed out that amphibole analyses conform to the formula $R''SiO_3, R = Ca,Mg,Fe,Mn,Na_2$ and K_2, plus varying proportions of Al_2O_3 (and Fe_2O_3), which formulas, however, do not apply to arfvedsonite and related minerals of the amphibole group, rich in soda and sesquioxides. In their essential features the formulas of Tschermak and Rammelsberg are alike, $Ca(Mg,Fe)_3Si_4O_{12}$ of Tschermak being equivalent to $4RSiO_3$, and the alumo-silicate molecules $(Ca,Mg)_2$-$Al_4Si_2O_{12}$ to $2RSiO_3 + 2Al_2O_3$. They differ in that Tschermak regards the alkalies as belonging to molecules like $Na_2Al_2Si_4O_{12}$, respectively $Na_2Fe_2Si_4O_{12}$, while Rammelsberg recognized Na_2SiO_3 as isomorphous with $CaSiO_3$ and $MgSiO_3$. Neither of them take into account water and fluorine, which, as will be shown, are essential and often prominent constituents of amphibole and should not be disregarded.

Numerous other formulas have been suggested by various investigators, but these in general refer only to analyses of single specimens of amphibole, and it does not seem necessary to discuss them at the present time.

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* Lehrbuch der Mineralogie, 1894, p. 458.

† Mineralchemie, 1875, page 394.

Before presenting the new analyses and entering upon their discussion, it seems best to set forth certain premises which may well be taken into consideration.

In the first place, it may be noted that amphibole contains an unusually large number of constituents, SiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, H_2O and F, among which are metallic elements having valences of three, two and one, and if any reasonable formula is to be proposed there must be some satisfactory disposition made of hydrogen and fluorine. For a mineral having so many and such variable constituents, and likewise having them in very variable proportions, it seems reasonable to assume a *complex chemical structure.* Compare amphibole for example with chrysolite, and a marked difference is noted; the formula of the latter is $(Mg,Fe)_2SiO_4$, and, disregarding impurities, if constituents other than SiO_2, MgO and FeO are noted in the analyses, they are either NiO or MnO, which are readily explained as isomorphous with MgO. In what are generally regarded as simple chemical compounds only such constituents are to be found which are alike in valence and in grouping according to the periodic system, and thus conform to the ordinary law of isomorphism; for example, FeO and MnO ismorphous with MgO. It may be noted also that in general Na_2O is not isomorphous with either K_2O or CaO, nor CaO with MgO, such constituents when occurring together generally forming double salts. In amphibole, however, owing as it is believed to its complex chemical structure, or to what one of the present writers has called *mass effect*,* such unlike constituents as H_2O, Na_2O, CaO, MgO and Al_2O_3 are in some way brought into a molecule as isomorphous constituents or radicals, a result which we do not meet with nor expect to meet with in the case of simple chemical compounds.

Again, when we consider the great diversity in chemical composition of the various minerals of the amphibole group, including glaucophane, riebeckite and arfvedsonite, all of them being essentially alike in crystallization, in cleavage and in prismatic angle, it must be assumed that there is some controlling factor responsible for this similarity in crystallization, and it is believed that this controlling factor is *the acid.* From the composition of the simplest minerals of the group, tremolite and actinolite, it seems definitely proved that the amphiboles are salts of metasilicic acid, not necessarily H_2SiO_3, but some multiple of this. Tschermak has suggested $H_8Si_4O_{12}$ as the stoichiometrical formula of the amphibole acid, and there are reasons for believing that this, or some multiple of it, is correct. It is to be regretted that at the present time there is

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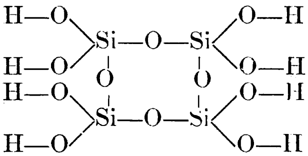
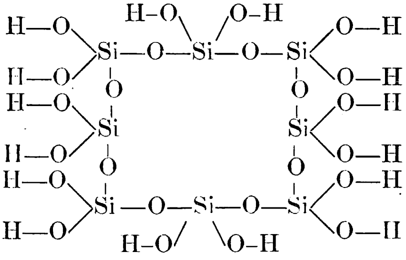
* This Journal, xiv, 211, 1902.

no means of determining the size of the molecule of a crystallized solid. Metasilicates are naturally and readily written structurally as ring formulas, and although such formulas are wholly hypothetical they are at least suggestive and hence useful. If $H_8Si_4O_{12}$ is the formula of the amphibole acid, or perhaps $H_{16}Si_8O_{24}$, natural ways of expressing these graphically would be as follows:





Although wholly incapable of proof, it is altogether within the bounds of reason to believe that the amphibole acid has a ring structure, and that as in organic chemistry we have a benzol ring which plays so important a rôle in a vast number of compounds, so in mineral chemistry we may speak of a probable *amphibole ring*, carrying with it a certain controlling force which conditions a kind of crystallization recognized as characteristic for the amphibole group of minerals. As will be pointed out later, calcium atoms replace one quarter of the hydrogen of the amphibole acid, and it may be that the position of the particular hydrogen atoms replaced by calcium is a matter of importance, just as in organic chemistry the ortho-, meta- or para-positions in the benzol ring are determining factors.

As has already been stated, it is believed that amphibole has a complex molecular structure; it is not readily made artificially and if fused and allowed to cool there result simple substances, especially pyroxene. If the ring theory is correct, it may be assumed that by fusion the amphibole ring is broken down and is incapable of reformation under ordinary conditions of heat and pressure.

To our knowledge amphibole has only once been made artificially, and this result was achieved by von Chrustchoff.* The accomplishment of this brilliant and too little known experiment is so important and throws so much light upon the

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*Neues Jahrbuch 1891, 2, page 86. [In a recent article entitled, "Minerals of the Composition $MgSiO_3$; Case of Tetramorphism" (this Journal, Nov. 1906), Messrs. E. T. Allen, F. E. Wright and J. K. Clement have described the synthesis of orthorhombic and monoclinic forms of pyroxene and amphibole. The monoclinic amphibole was obtained with considerable difficulty and only in small amounts and in microscopic crystals. W. E. FORD.]

mode of formation of amphibole in nature that a brief outline of von Chrustchoff's method may be given here to advantage. In his experiment aqueous solutions of silica, alumina and ferric hydroxide were taken, carefully prepared by dialysis, freshly precipitated ferrous hydroxide, lime water, magnesium hydroxide suspended in water and sodium and potassium hydroxides; these constituents when brought together made a rather stiff gelatinous mass, which was placed in several glass bombs *(Birne)*: the bombs were then exhausted, hermetically sealed, and continuously heated for a period of three months at a temperature of 550° C. Several of the bombs exploded, but three of them withstood the severe strain, and on opening these there was found a brownish deposit containing well formed crystals 1^{mm} long and $\frac{1}{4}^{mm}$ thick, of brilliant luster, dark color and showing forms commonly observed on amphibole; *b* (010), *m* (110) and *r* (011). The prismatic angle could only be measured approximately, but $r \wedge r'$, $011 \wedge 0\bar{1}1$, gave with exactness 31° 32′, which is like one of the fundamental amphibole angles of Koksharov. An analysis of the crystals is here given and for comparison the results obtained by Stanley from the black amphibole (hornblende) from Edenville, N. Y.

	Artificial Crystals		Edenville	
Sp. gr.	3·245		3·284	
SiO_2	42·35		41·99	
TiO_2	----		1·46	
Al_2O_3	8·11	16·02	11·62	14·29
Fe_2O_3	7·91		2·67	
FeO	10·11	24·44	14·32	25·74
MnO	....		0·25	
MgO	14·33		11·17	
CaO	13·21		11·52	
Na_2O	2·18		2·49	
K_2O	1·87		0·98	
H_2O (loss on ignition)	0·91		0·53	
(H_2O at 110°)	----		0·08	
F	----		0·80	
	100·98		99·83	

The two analyses are very much alike, especially when it is taken into consideration that the higher Al_2O_3 and FeO of the Edenville material are offset respectively by lower Fe_2O_3 and MgO.

The failure to make amphibole by ordinary methods of synthesis, and the success of von Chrustchoff's experiment indicate clearly that the conditions necessary for the formation of the mineral are those which are obtained with difficulty in a laboratory, namely the combined action of heat and pressure, maintained for a considerable period of time; conditions, however, of common occurrence in nature. Amphibole is undoubtedly a mineral which commonly owes its origin to what is known as pneumatolitic action, that is to aqueous vapors and other gases working under the combined action of heat and pressure. In minerals formed under such conditions are found water with hydrogen playing the rôle of a metal, hydroxyl, fluorine and, as in the case of tourmaline, boron. Many of the minerals have complicated chemical formulas, for which possibly the mode of formation is responsible, pressure and other agencies giving rise to molecular structures more intricate than are generally met with. In several of these pneumatolitic minerals, amphibole, tourmaline and the micas for example, there may be noted the occurrence of a large number of elements, of varying valences and evidently occurring in some way as isomorphous constituents.

In spite of the fact that pneumatolitic minerals have been produced with difficulty, if at all, by synthetic methods, it is reasonable to suppose from their common occurrence in nature that they might be produced with comparative ease if the right conditions could be obtained. It is probable that with a suitable container provided with electric heating appliances, within which a high pressure could be maintained, the conditions favorable for the synthetic production of numerous pneumatolitic minerals might be attained and satisfactory results expected.

To recapitulate, our premises are as follows:—Amphibole is presumably a mineral of complex molecular structure, a salt of some multiple of H_2SiO_3, very probably of an acid characterized by a ring structure, but the number of silicon atoms contained in the ring it is impossible to state. This much also seems probable, that the number of silicon atoms in the amphibole molecule, and their arrangement, whatever that may be, exert such a controlling influence that by virtue of *mass effect* the hydrogen atoms of the acid may be replaced by elements of different valences and by radicals without exerting any appreciable effect upon the crystalline form.

Selection and preparation of materials for the new analyses.—The endeavor has been made to select materials representing a wide range in chemical composition and also with the view of having the samples prepared for analyses as pure as possible. Most of the specimens have been selected from the Brush Collection. As a rule they were well crystallized and the materials were at first carefully selected by hand picking; subsequently they were pulverized and sifted to an uniform grain, suspended in heavy solutions and from each a portion was selected which floated and sank within narrow limits. The heavy solutions used were potassium-mercuric iodide for the lighter and barium-mercuric iodide for the heavier varieties of amphibole. In every case the powders were washed with great care to remove every trace of the heavy solutions; they were also examined under the microscope to note the presence of any possible impurities. It may be stated with confidence that all of the materials which have been analyzed were of the utmost possible purity.

Method of Analysis.—The methods employed in making the analyses were like those for a long time in use in the Sheffield Laboratory, and essentially the suggestions as outlined by Clarke and Hillebrand* and by Washington† were followed. The analyses were made by Stanley, and before starting on them considerable time was spent in gaining familiarity with the methods of separation, for which purpose numerous artificial mixtures were made and analyzed. In cases where much iron and alumina were present the separation from magnesia was made by means of a double basic acetate precipitation. Fluorine was determined by the Berzelius method as outlined by Penfield and Minor,‡ and from experiments made with artificial mixtures containing the same constituents in about the same proportions as in amphibole it is probable that the results obtained for fluorine are all too low by about 0·10 to 0·15 per cent. Water was in all cases determined by the closed-tube method described by one of the present writers.§ In several cases, especially in the early part of the investigation, analyses of the same material were repeated four or six times in order to gain the greatest possible accuracy in the determinations. With few exceptions the determinations were always made in duplicate.

New Analyses and discussion of results:—Amphibole occurs in several distinct varieties, some of which are conveniently designated by names, and it seems best to take up the analyses in groups, commencing with the simplest types. The discussion of the analyses is based upon the ratios derived by dividing the percentages of the several constituents by their molecular weights. In the case of fluorine the percentages are divided by twice the atomic weight, in order to make the quotients comparable to those obtained from the percentages of H_2O; two fluorine atoms being equivalent to two hydroxyl radicals, represented in the analyses by the hydrogen atoms of H_2O. Hydrogen unquestionably plays a double rôle in amphibole and numerous other minerals having a complex

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* Analyses of Rocks and Analytical Methods, U. S. G. S. Bull. 148.

† The Chemical Analysis of Rocks.

‡ This Journal, xlvii, 387, 1894.

§ This Journal, xlviii, 31, 1894.

chemical structure. In part it goes with oxygen to form hydroxyl (OH), which radical has the character of an unmetallic, acid-forming element, as shown by its isomorphism with fluorine; in part also hydrogen is basic like a metal, H_2 being isomorphous with Na_2, Ca or Mg, or, in accordance with our conventional method of expressing analyses, H_2O is isomorphous with Na_2O, CaO, MgO, etc. From the results of the determination of water in analyses, there seems at the present time no way of determining how much hydrogen is to be ascribed to hydroxyl and how much is basic. In both cases the resulting water is driven off only on intense ignition. In the present analyses so much confidence is felt in the purity of the materials analyzed that the question of hydroscopic water or water resulting from alteration does not enter into the calculations, nor is water of crystallization present.

From the supposed mode of formation of amphibole by pneumatolitic action, both hydroxyl and fluorine enter into the composition of the mineral and must be reckoned with the same as other constituents: Water as a base, isomorphous with Na_2O, CaO, MgO, etc., must also be taken into consideration, and this is such an important matter that it seems best to refer to a simple yet striking example encountered by one of the writers* in the investigation of a very pure variety of anthophyllite. In the analysis water was first estimated as loss at a low red heat and found to be only 0·19 per cent. On completing the analysis the summation was unsatisfactory, as was also the ratio of SiO_2 to the bases, FeO,MgO with traces of MnO and CaO. In endeavoring to find an explanation for the defects of the analysis and its failure to give a good ratio, some of the powdered mineral was heated with a blast-lamp in a closed tube, when at a very high temperature abundant water was given off. This water, amounting to 1·67 per cent, brought the summation of the analysis to 99·99 and the ratio of SiO_2 to $FeO+MnO+MgO+CaO+H_2O$ became 1·00 : 0·997. Therefore in this comparatively simple combination of silica with protoxide bases there can be no question but that H_2O is isomorphous with MgO and FeO.

In addition to the ratio of silica to the protoxide bases, it will be interesting to note the relative proportion of the several bases present: This is conveniently expressed in per cents and is given with each analysis.

The analyses are as follows:

TREMOLITE.

Of this material, representing the simplest type of amphibole, two analyses have been made. The specimens selected

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* This Journal (3), xl, p. 394, 1890.

for study were purposely chosen from quite widely separated regions, and because of their being very unlike in appearance and mode of occurrence.

I. *Tremolite from Richville, near Gouverneur, New York.*—This locality is the one famous for its brown tourmalines, known to collectors the world over. The specimen consisted of a mass of large white crystals, some showing distinct outline and the ordinary forms, *m* (110), *b* (010) and *r* (011). When broken up the fine splinters were perfectly transparent. The material used for analysis floated on the heavy solution at 3·002 and sank at 2·992; the average specific gravity, therefore, may be taken as 2·997.

The results of the analyses are as follows—

	I	II	Average	Ratio	Per cents of protoxide bases	
SiO_2	57·47	57·43	57·45	·957		
TiO_2	----	----	----			
Al_2O_3	1·28	1·32	1·30	·014		
Fe_2O_3	·18	·18	·18			
FeO	·22	·22	·22	·958	0·3	65·2
MnO	·07	---	·07		0·1	
MgO	24·87	24·83	24·85		64·8	
CaO	12·84	12·94	12·89		24·0	25·8
K_2O	·49	·58	·54		0·7	
Na_2O	·68	·66	·67		1·1	
H_2O	1 30	1·20	1·16		6·9	
F_3	·77		·77		2·1	
					100·00	
Loss at 110°			·09			
			100·19			
$O = F_2$			·32			
			99·87			

The ratios of this and the following analyses will be discussed later.

II. *Tremolite from Lee, Massachusetts.*—This material consisted of bladed crystals, showing only prisms, somewhat striated, embedded in a grayish-white, fine-grained, crystalline, dolomite-marble. As far as was observed, the crystals never show distinct terminal faces. The tremolite crystals have a grayish white color, but small fragments are colorless and transparent. The crystals were first carefully selected by hand and after pulverizing and sifting to a uniform grain, the powder was treated for a while with warm, dilute hydrochloric acid to insure removal of possible traces of attached dolomite.

The material used for analysis floated on the heavy solution at 2·984 and sank at 2·975, the average being 2·980. The results of the analysis are as follows:—

	I	II	Average	Ratio		Per cents of protoxide bases	
SiO_2	57·61	57·78	57·69	·961	·963		
TiO_2	·14	·14	·14	·002			
Al_2O_3	1·85	1·75	1·80	·018	·018		
Fe_2O_3	·00	·00	·00	·000			
FeO	·55	·55	·55	·007	·954	0·7	64·2
MnO	trace	trace	trace	·000		0·0	
MgO	24·12	24·12	24·12	·606		63·5	
CaO	13·07	13·30	13·19	·236		24·7	25·7
K_2O	·22	----	·22	·002		0·2	
Na_2O	·48	----	·48	·008		0·8	
H_2O	1·76	1·61	1·56	·087		9·0	
F_2	·37	----	·37	·011		1·1	
Loss at 110°			·10			100·0	
			100·22				
		$O=F_2$	·15				
			100·07				

ACTINOLITE.

Of the green variety of amphibole, characterized by a low percentage of sesquioxides and commonly known as *actinolite*, four varieties have been analyzed. As regards localities, association and mode of occurrence they are as widely separated as possible.

III. *Actinolite from Greiner in Tyrol. Specimen No. 349, Brush Collection.*—This is one of the well known localities, where crystals of a fine, dark-green color, showing the combination of the prism *m* (110) and pinacoid *b* (010), occur imbedded in talc. To obtain material for analysis the crystals were first carefully selected by hand, and as they were found to be coated with a fine talcose powder, they were treated for a while with a mixture of warm dilute hydrofluoric and hydrochloric acids, which left them clean and brilliant. When broken up and sifted to an uniform grain the fragments were found to be wonderfully pure when studied with the microscope. A very small proportion of the particles were found to contain minute black grains, presumably of magnetite, but these being heavier were removed by treatment with the heavy solution. The material for analysis floated at 3·058 and sank at 3·036, the average specific gravity being 3·047.

The results of the analysis are as follows:—

	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	56·13	56·36	56·25	·938	·938		
TiO_2	·00	----	·00	---			
Al_2O_3	1·24	----	1·24	·012	·017		
Fe_2O_3	·74	·82	·78	·005			
FeO	5·50	----	5·50	·076	·935	8·1	65·5
MnO	·48	----	·48	·007		0·9	
MgO	21·18	21·20	21·19	·529		56·5	
CaO	12·15	12·00	12·08	·216		23·1	23·7
K_2O	·29	·28	·28	·003		0·3	
Na_2O	·19	·18	·19	·003		0·3	
H_2O	1·89	1·73	1·81	·100		10·7	
F_2	·04	----	·04	·001		0·1	
			99·84			100·0	

The amount of fluorine in this analysis is so small that a distinct qualitative test could not be obtained.

IV. *Actinolite from Russell, St. Lawrence Co., New York. Specimen No. 424, Brush Collection.*—The specimen chosen for analysis is typical for amphibole found throughout quite an extensive area in St. Lawrence Co. The piece analyzed consists of crystals varying from 2 to 4^{cm} in diameter, having the forms shown in figure 1, *m* (110), *e* (130), *b* (010), *r* (011), and occasionally *i* (031). The color of the crystals is dark green, but small splinters have a rather light color and are transparent. The powdered material floated at 3·102 and sank at 3·081, the average being 3·092. The results of the analysis are as follows:—

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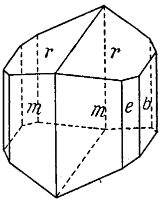

	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	54·85	54·75	54·80	·913	·914		
TiO_2	·10	----	·10	·001			
Al_2O_3	2·56	2·59	2·58	·025	·041		
Fe_2O_3	2·40	2·60	2·50	·016			
FeO	4·68	4·82	4·75	·066	·913	7·30	63·2
MnO	trace	----	trace	----		----	
MgO	20·24	20·36	20·30	·507		55·9	
CaO	12·19	11·97	12·08	·216		23·8	25·5
K_2O	·24	----	·24	·003		0·3	
Na_2O	·82	----	·82	·013		1·4	
H_2O	1·56	1·64	1·60	·088		9·1	
F_2	·77	----	·77	·020		2·2	
Loss at 110°			·11				
						100·0	
			100·65				
		$O = F_2$	·32				
			100·33				

V. *Actinolite from the Mines of Kragerö, Norway.*—The material for analysis was taken from a large, striated, prismatic crystal, without terminal faces, which was presented to the Brush Collection by Prof. W. C. Brögger of Christiania. The color of the large crystal was dark olive-green, but fragments were light colored. The material floated at 3·180, sank at 3·094, the average being 3·137. The results of the analysis follow:—

	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	57·07	51·64	51·85	·864	·880		
TiO_2	1·26	....	1·26	·016			
Al_2O_3	4·36	4·37	4·36	·043	·059		
Fe_2O_3	2·58	----	2·58	·016			
FeO	5·46	----	5·46	·075		8·6	64·8
MnO	·33	·37	·35	·005		0·5	
MgO	19·35	19·61	19·48	·487		55·7	
CaO	10·40	10·81	10·60	·189		21·6	26·1
K_2O	·35	----	·35	·004		0·5	
Na_2O	2·15	---	2·15	·035		4·0	
H_2O	1·35	1·33	1·21	·067		7·7	
F_2	·46	----	·46	·012		1·4	
Loss at 110°			·13			100·0	
			100·24				
		$O = F_2$	·22				
			100·02				

VI. *Actinolite from Pierrepont, St Lawrence Co., New York.*—The specimen from which material for analysis was taken was collected by one of the writers while engaged in mineralogical work for the U. S. Geological Survey, and thanks are

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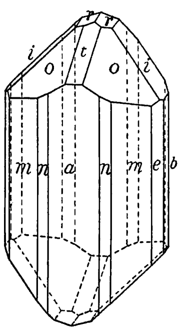

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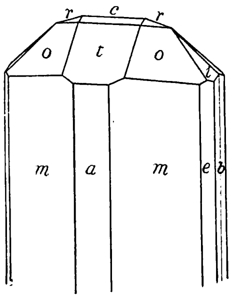


due to the Director of the Survey for permission to use the material in any way for scientific purposes. The habit of the crystals is unusual and is shown by figure 2, but, the crystals being attached, doubly terminated ones have not been observed. Figure 3 represents one end of a twin crystal. The forms which are quite numerous for amphibole are: *a* (100), *b* (010), *c* (001), *n* (310), *m* (110), *e* (130) *r* (011), *i* (031), *t* (101) and *o* (121). It was throught that perhaps the unusual development of these crystals might be due to some peculiarity in chemical composition, but the results of the analysis have not borne out this supposition. The color of the crystals is a dark greenish-black. The powder used for analysis floated at 3·115 and sank at 3·107, the mean specific gravity being 3·111.

	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	52·58	52·05	52·31	·872	·876		
TiO_2	·25	....	·28	·004			
Al_2O_3	2·72	2·66	2·69	·026	·045		
Fe_2O_3	3·32	2·85	3·09	·019			
FeO	6·83	6·53	6·68	·093	·917	10·1	63·8
MnO	·70	....	·70	·010		1·1	
MgO	19·12	19·42	19·27	·482		52·6	
CaO	11·88	11·88	11·88	·212		23·1	25·0
K_2O	·50	....	·50	·005		·6	
Na_2O	·78	....	·78	·012		1·3	
H_2O	1·55	1·45	1·42	·079		8·6	
F_2	·93	....	·93	·024		2·6	
Loss at 110°			·08			100·0	
			100·59				
		$O = F_2$	·39				
			100·20				

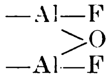
Discussion of the Tremolite and Actinolite Analyses:—Since tremolite and actinolite constitute a group by themselves, differing somewhat in molecular ratios from other varieties containing high percentages of sesquioxides (Al_2O_3 and Fe_2O_3) which will be considered later, it seems best at this point to discuss the analyses already described. Attention may first be called to the ratio of SiO_2 to the protoxide bases $R''O$, the latter including K_2O, Na_2O, H_2O and F_2. The ratios are as follows:—

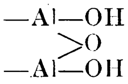
			SiO_2	:	R'''_2O_3	:	$R''O+F_2$	SiO_2	:	$R''O+F_2$
Tremolite	I.	Richville	·957	:	·014	:	·958	1	:	1·001
	II.	Lee	·963	:	·018	:	·954	1	:	·991
Actinolite	III.	Greiner	·938	:	·017	:	·935	1	:	·997
	IV.	Russell	·914	:	·041	:	·908	1	:	·993
	V.	Kragerö	·880	:	·059	:	·874	1	:	·993
	VI.	Pierrepont	·876	:	·045	:	·923	1	:	1·05

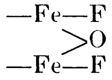
In the first five analyses the ratios of $SiO_2 : R''O+F_2$ are almost exactly as 1 : 1, and attention may be called to the fact that such close approximations to an exact ratio are seldom met with in mineral analyses. It may be concluded therefore from the ratios that the materials were very pure, the analyses exceptionally good, and that both water and fluorine, which have been generally disregarded in previous calculations, must be taken into consideration. Five such results preclude the possibility that the close agreement of the ratios to 1 : 1 is a matter of accident. Analysis VI is irregular in that it shows an excess of $(R''O+F_2)$ over SiO_2. This may be due to defects in the analysis, to possible impurities in the material, or this special variety may be a transition between actinolite and hornblende, the latter, as will be shown later, being characterized by having an excess of $(R''O+F_2)$ over SiO_2. Analyses IV, V VI, the ratios derived from them, and the percentages of the several constituents are so nearly alike, that it seems best to class the mineral from Pierrepont as actinolite. The analysis needs revision.

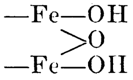
Except as regards fluorine, the ratios derived from the six analyses confirm the theory of Rammelsberg, namely, that the composition is $RSiO_3 + R_2O_3$, the $RSiO_3$ including $MgSiO_3$, $FeSiO_3$, $CaSiO_3$ and Na_2SiO_3, while considerable H_2SiO_3, which Rammelsberg left out of consideration, must also be included. The ratios also confirm in a general way the theory of Tschermak except that considerable hydrogen would have to be brought into the formulas and some provision made for fluorine. Moreover the ratios indicate clearly that the idea advanced by Tschermak, that sodium is present as a molecule, $Na_2Al_2Si_4O_{12}$, is quite untenable, since for every Na_2O there would have to be deducted $1Al_2O_3$ and $4SiO_2$, which would deplete the total silica and destroy the 1 : 1 ratio.

In a large number of minerals it has been shown that fluorine and the isomorphous hydroxyl unite with metallic elements to form radicals, thus $(MgF)'$, or $(MgOH)'$, univalent, and $(AlF)''$ or $(AlOH)''$ bivalent, and it seems probable that fluorine, and to some extent hydroxyl, enter in some way into the amphibole molecule in combination with trivalent aluminium and iron. It is possible in one way to account for the presence of both R_2O_3 and fluorine without destroying the 1 : 1 ratio shown by the analyses. Thus, for example, the constituents Al_2O_3 and Fe_2O_3 may be regarded as combined with F and OH to form the following radicals:



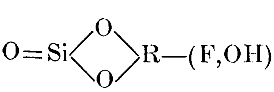


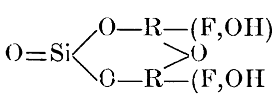


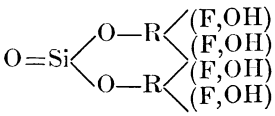


The foregoing radicals are bivalent and, as may be seen, the addition of F_2 to the protoxide ratios means the introduction of Al_2 (or Fe_2) into the molecule, and when F_2 fails or is not sufficient to satisfy all of the sesquioxides, $(OH)_2$, derived from H_2O, accomplishes the same result. If, therefore, the ideas as set forth on page 28 are correct, namely that amphibole is a salt of a complex metasilicic acid, the assumption is now made that some of the hydrogen atoms of the acid are replaced by bivalent radicals, containing aluminium and ferric iron in combination with fluorine and hydroxyl as given above. These bivalent radicals therefore are regarded as isomorphous with Fe and Mg. It may be asked why the radicals $[R_2'''OF_2]''$ and $[R_2'''O(OH)_2]''$ have been selected instead of others? for example, $[R'''F]''$ or $[R'''F_2]'$, and their respective hydroxyl equivalents, and the answer is simply because only the former satisfy the 1 : 1 ratio of silica to protoxide bases shown by the analyses.

Since, however, the amounts of Al_2O_3 and Fe_2O_3 in tremolite and some varieties of actinolite are small, the assumption of either of the radicals $[R'''(F, OH)]''$ or $[R'''(F, OH)_2]'$ would not materially affect the ratios in some cases. For the sake of comparison the possible fluor-hydroxyl radicals of trivalent elements in combination with metasilicic acid may be expressed graphically as follows:







According to the first assumption, bringing R''' into the molecule as a bivalent radical $[R-(F, OH)]''$, the protoxides as given on page 36 would be increased; according to the last $[R_2(F, OH)_4]''$ the protoxides would be diminished, the resulting ratios being as follows:

	SiO_2	:	$R''O+[R'''(F, OH)]''O$	SiO_2	:	$R''O+[R'''(F.OH)_2]'_2O$
I	1	:	1·02	1	:	0·98
II	1	:	1·01	1	:	0·97
III	1	:	1·02	1	:	0·98
IV	1	:	1·04	1	:	0·95
V	1	:	1·06	1	:	0·93

The ratios are not bad in the first three analyses, but in the last two they are unsatisfactory and, moreover, in analysis V there is not sufficient fluorine and hydroxyl to satisfy the last assumption. The burden of proof rests with the more exact ratios as given on page 36, and the assumption that the sesquioxides enter the metasilicate molecule as bivalent radicals corresponding to $[R_2'''O(FOH)_2]'''$.

It is interesting to note to what extent the hydrogen atoms of the amphibole acid are replaced. According to the long-accepted formula for tremolite, $Mg_3CaSi_4O_{12}$, three-quarters, or 75 per cent, are replaced by Mg and the remaining quarter by Ca, while in actinolite the isomorphous Fe, Mn and Mg together have been regarded as replacing three-quarters of the hydrogens. The replacement, expressed in per cents, as they appear in the analyses, are as follows:

	I	II	III	IV	V
$[Fe+Mn+Mg]''$	65·2	64·2	65·5	63·2	64·8
$[Ca+K_2+Na_2]''$	25·8	25·7	23·7	25·5	26·1
$[R_2'''O(F,OH)_2]''$	1·5*	1·9	1·8	4·5	6·7
H_2 in excess of (OH)	6·9	8·2	9·0	6·8	2·4
Ca alone	24·0	24·7	23·1	23·8	21·6

* A slight excess of fluorine (0·23%) in the analysis. See page 50.

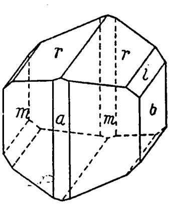
It may be seen from the foregoing table that (Fe+Mn+Mg) never make up 75 per cent of the total hydrogen replacement, and that the figures are remarkably constant at about 65 per cent. Ca alone never replaces 25 per cent of the total hydrogens, but if there are added to the Ca the small amounts of alkali metals present, K_2 and Na_2, the near approach to 25 per cent is remarkable; in analysis II, where Ca alone is low, the deficiency is made up by a rather high percentage of Na_2O (2·15%), while in the remaining analyses it ranged frem 0·19 to 0·82, averaging 0·54%. In all cases K_2O was low, ranging from 0·22 to 0·54 and averaging 0·33%. The trivalent elements, Al and Fe, presumably entering into the amphibole molecule as bivalent fluor-hydroxyl radicals, are quite variable, and so also are the amounts of hydrogen in excess of that required in each analysis for combination as hydroxyl with Al and Fe.

EDENITE — PARGASITE — HORNBLENDE.

The name *edenite* has been employed to designate light-colored varieties of amphibole containing considerable alumina. Chemically there are analogous dark-colored varieties sometimes called *pargasite*, containing high percentages of iron, and both kinds doubtless grade imperceptibly into one another and also into actinolite. The names are not very characteristic nor significant, and perhaps the designation of these various varieties as *hornblende* is more satisfactory than the attempt to make use of several names. As will be shown, the hornblendes are characterized by having a somewhat different ratio of SiO_2 to the protoxide bases than that determined for tremolite and actinolite.

VII. *Hornblende from Renfrew, Ontario, Canada.*—The crystal analyzed was of an unusually black color and brilliant luster, showing the forms *a* (100), *b* (010), *m* (110), *r* (011) and *i* (031), figure 4. The specimen is No. 487 of the Brush Collection. Fragments used for analysis floated at 3·330 and sank at 2·249, the mean specific gravity being 3·290. The results of the analysis follow :—

4



	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	43·92	43·60	43·76	·728	·738		
TiO_2	·78	----	·78	·010			
Al_2O_3	8·35	8·31	8·33	·081	·124		
Fe_2O_3	6·99	6·80	6·90	·043			
FeO	10·40	10·54	10·47	·146	·797	18·3	58·7
MnO	·50	----	·50	·007		0·9	
MgO	12·67	12·60	12·63	·315		39·5	
CaO	9·86	9·82	9·84	·176		22·1	30·8
K_2O	1·28	----	1·28	·014		1·8	
Na_2O	3·43	----	3·43	·055		6·9	
H_2O	·75	·55	·65	·036		4·5	
F_2	1·82	----	1·82	·048		6·0	
Loss at 110°			·10			100·0	
			100·49				
		$O = F_2$	·76				
			99·73				

VIII. *Hornblende from Edenville, Orange Co., New York.*—Crystals from this locality occur large and of a black color, very closely resembling those from Renfrew; the forms also, *b*, *m*, *r* and *i* are frequently developed as in figure 4. The material used for analysis floated at 3·291 and sank at 3·278, the average being 3·285. The results of the analysis follow :

	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	41·92	42·06	41·99	·699	·717		
TiO_2	1·46	----	1·46	·018			
Al_2O_3	11·73	11·51	11·62	·112	·129		
Fe_2O_3	2·54	2·80	2·67	·017			
FeO	14·28	14·36	14·32	·199	·798	25·0	60·4
MnO	·25	----	·25	·003		·4	
MgO	11·21	11·13	11·17	·279		35·0	
CaO	11·50	11·54	11·52	·206		26·0	32·2
K_2O	·92	1·04	·98	·010		1·2	
Na_2O	2·66	2·32	2·49	·040		5·0	
H_2O	·66	·56	·61	·038		4·8	
F_2	·80	----	·80	·021		2·6	
Loss at 110°			·08			100·0	
			99·96				
		$O = F_2$	·33				
			99·63				

IX. *Hornblende from Cornwall, Orange Co., New York.*—This is a very black hornblende occurring in masses larger than a walnut and without crystalline outline, imbedded in a rather coarse aggregate of quartz and feldspar. It was originally described by Beck* in 1842 as a new species to which the name *Hudsonite* was given. It was classed by J. D. Dana† under pyroxene and was analyzed by Brewer‡ and by Smith and Brush.§

It has recently been reinvestigated by Weidman,‖ the material used being a specimen from the Brush Collection No. 139, sent to Professor Brush in 1853 by S. R. Horton, who first found the mineral and supplied Beck with specimens for his original description. The prismatic angle $m \wedge m$ was measured by Penfield and found to be 55° 31′. The optical properties are described in detail by Weidman and he also gives a new analysis by J. L. Nelson of the chemical department of the University of Wisconsin. On testing the mineral in a closed tube it was found that the water given off at a high temperature was decidedly acid and accompanied by a deposition of silica, indicating the presence of fluorine, hence it has been possible to make Nelson's analysis more complete by making a determination of fluorine in the material, 0·27 per cent being found. It may also be added that the presence of fluorine in the mineral was suspected because the analysis did not conform to the new ideas concerning the ratios it should

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* Min. N. Y. 405, 1842.

† System of Mineralogy, 2d ed., 1844.

‡ Dana's Mineralogy, 3d ed., 269.

§ This Journal, xvi, 1853.

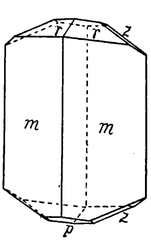
‖ Ibid., xv, 227, 1903.

give. The analysis of Nelson, modified by the introduction of 0·27 per cent of fluorine, follow :—

		Ratios		Per cents of protoxide bases	
SiO_2	36·86	·614	·627		
TiO_2	1·04	·013			
Al_2O_3	12·10	·119	·165		
Fe_2O_3	7·41	·046			
FeO	23·35	·324	·709	45·9	53·2
MnO	0·77	·005		·7	
MgO	1·90	·047		6·6	
CaO	10·59	·189		26·6	35·7
K_2O	3·20	·013		1·8	
Na_2O	1·20	·052		7·3	
H_2O	1·30	·072		10·1	
F	·27	·007		1·0	
	99·99			100·0	
$O-F_2$	·11				
	99·88				

X. *Hornblende from Monte-Somma, Italy.*—The material analyzed was taken from a specimen showing an aggregate of small greenish black crystals, many of them terminated by faces having a brilliant luster, developed as shown in figure 5, the forms being, *m* (110), considerably striated, *r* (011), *p* ($\bar{1}01$) and sometimes *z* ($\bar{1}21$). The material used for analysis floated at 3·310 and sank at 3·255, the average specific gravity being 3·283. The results of the analysis follow :—

5



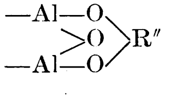
	I	II	Average	Ratios		Per cents of protoxide cases	
SiO_2	39·41	39·55	39·48	·658	·662		
TiO_2	·30	....	·30	·004			
Al_2O_3	12·71	13·27	12·99	·127	·172		
Fe_2O_3	7·30	7·21	7·25	·045			
FeO	10·73	....	10·73	·149	·759	19·6	59·3
MnO	1·14	·85	1·00	·014		1·9	
MgO	11·76	11·17	11·47	·287		37·8	
CaO	12·10	11·95	12·01	·214		28·2	35·1
K_2O	2·39	...	2·39	·025		3·3	
Na_2O	1·72	1·68	1·70	·027		3·6	
H_2O	·82	·95	·76	·042		5·5	
F_2	·05	....	·05	·001		·1	
Loss at 110°			·12				
			100·25			100·0	
		$O=F_2$	·02				
			100·23				

The hornblendes represented by analyses VI to X constitute a group by themselves, which may next be considered. They differ from the tremolite-actinolite group in that the ratio of $SiO_2 : RO$, instead of being as 1 : 1, indicates an excess of RO over SiO_2 and with the increase of RO there is a corresponding increase in the amounts of Al_2O_3 and Fe_2O_3. The relations are best shown in the accompanying tables, where the R_2O_3 quotients, (the sum of the results obtained by dividing the percentages of Al_2O_3 and Fe_2O_3 by the corresponding molecular weights) are given together with the $SiO_2 : RO$ ratios, RO including Na_2O, K_2O, H_2O and F_2.

		R_2O_3 quotients	SiO_2		RO
VI.	Pierrepont	·045	1	:	1·05
VII.	Renfrew	·124	1	:	1·08
VIII.	Edenville	·129	1	:	1·10
IX.	Cornwall	·165	1	:	1·11
X.	Mte. Somma	·172	1	:	1·14

The first analysis of this group forms a connecting link between the actinolite and hornblende groups. If it is compared with analysis V no essential differences will be found; it is only when the ratios are examined that a slight excess of RO is noted in the mineral from Pierrepont, and this occurs with a smaller R_2O_3 quotient than that found in the actinolite from Kragerö; as previously stated, the two groups grade imperceptibly into one another. The other analyses are, however, considerably different from any thus far considered; they are all of dark green to black varieties, the color due to the presence of iron; the percentages of sesquioxides are high, about 20 per cent in IX and X, and the excess of RO as shown by the ratios is very noticeable. Another marked difference is seen on comparing the silica percentages; starting with about 57·5 per cent in tremolite, it falls below 37 per cent in analysis IX.

It is evident that if the minerals of the amphibole group are all to be regarded as salts of one acid, we must in some way be able to account for the introduction into the amphibole molecule of both sesquioxides and increasing amounts of protoxides. This may be done by assuming in addition to the fluor-hydroxyl radical $[R'''_2O(F,OH)_2]''$ thus far considered, some other radicals containing both R_2O_3 and RO. Thus there might be considered the following alumina and the corresponding ferric iron radicals.



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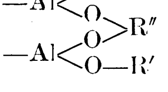
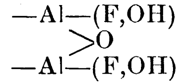
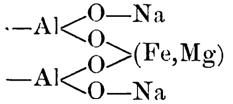


The attempt will now be made to show that by assuming the existence of certain bivalent basic radicals of the type just indicated, and regarding them as replacing the hydrogen atoms of the amphibole acid, a similarity may be found between these basic hornblendes and the members of the tremolite-actinolite group. There will first be deducted from the ratios the alumo, fluor-hydroxyl radical



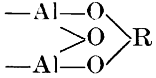
$\begin{array}{l}-\mathrm{Al}-(\mathrm{F,OH}) \\ \quad >\mathrm{O} \\ -\mathrm{Al}-(\mathrm{F,OH})\end{array}$

, the same as in the tremolite group. Next there will be deducted a radical of the type



$\begin{array}{l}-\mathrm{Al}<^{\mathrm{O-Na}}_{\mathrm{O}}>(\mathrm{Fe,Mg}) \\ -\mathrm{Al}<^{\mathrm{O}}_{\mathrm{O-Na}}\end{array}$

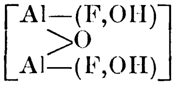
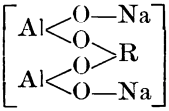
and in most cases these two radicals may be so chosen as to satisfy or include all of the sesquioxides, and leave the protoxide base in sufficient amount to form $RSiO_3$. In one analysis (X) a third radical seems necessary



$\begin{array}{l}-\mathrm{Al}-\mathrm{O} \\ \quad >\mathrm{O}>\mathrm{R} \\ -\mathrm{Al}-\mathrm{O}\end{array}$

. To indicate the method of calculation; there will be deducted from the total ratio first the alumo, fluor-hydroxyl radical, with its equivalent of silica, thus SiO_2, Al_2O_3 and (F,OH) in the proportion 1 : 1 : 1, and next the basic radical with Al_2O_3, (Fe,Mg)O and Na_2O with its equivalent of silica in the proportion 1 : 1 : 1 : 1. It is then possible to calculate the proportion of the total hydrogen atoms replaced by the several bivalent radicals and the different bases, and attention may be called to the fact that calcium, helped out at times by traces of sodium and potassium, satisfies 25 per cent, or one quarter of the total hydrogen atoms of the amphibole acid, the same as in the tremolite group;—that this is a mere coincidence seems hardly possible, and it may be taken, it is believed, in support of the theory advanced. The results of calculation are as follows:—

Analysis VII, Renfrew, Canada.

	Ratios	 $\left[\begin{array}{l}\mathrm{Al}-(\mathrm{F,OH}) \\ \quad >\mathrm{O} \\ \mathrm{Al}-(\mathrm{F,OH})\end{array}\right]$ ″	Residue	 $\left[\begin{array}{l}\mathrm{Al}<^{\mathrm{O-Na}}_{\mathrm{O}}>\mathrm{R} \\ \mathrm{Al}<^{\mathrm{O}}_{\mathrm{O-Na}}\end{array}\right]$ ″	Residue	
$[Si,Ti]O_2$	·738	—·065	·673	—·059	·614	
$[Al,Fe]_2O_3$	·124	—·065	·059	—·059	----	
[Fe,Mn,Mg]O	·468		·468	—·059	·409	
CaO	·176		·176		·176	·186
$[K,Na]_2O$	·069		·069	—·059	·010	
H_2O	·036	—·065	·019		·019	
F_2	·048					
				Total RO=	·614	

The proportion of the various radicals and of the remaining bases in the foregoing analysis are as follows:—

	Ratios	Per cents
$[Al_2O(F,OH_2]''O$	·065	8·8
$[Al_2O_4RNa_2]''O$	·059	8·0
$[Fe,Mn,Mg]O$	·409	55·4
$[Ca,Na_2]O$	·186	25·2
H_2O	·019	2·6
	·738	100·0

From the foregoing interpretation it may be seen that all of the fluorine and about half of the hydrogen are needed to form the alumo, fluor-hydroxyl radical; that sodium is present in just about sufficient amount to form the second basic radical, and that calcium plus the trifling excess of sodium satisfies 25 per cent of the hydrogen atoms of the amphibole acid.

ANALYSIS VIII, EDENVILLE, N. Y.

	Ratios	$\left[\begin{array}{l}\text{Al—(F,OH)}\\ \quad >\text{O}\\ \text{Al—(F,OH)}\end{array}\right]''$	Residue	$\left[\begin{array}{l}\text{Al}<^{\text{O—Na}}_{\text{O}}>\text{R}\\ \text{Al}<^{\text{O}}_{\text{O—Na}}\end{array}\right]''$	Residue
$[Si,Ti]O_2$	·717	—·051	·666	—·078	·588
$[Al,Fe]_2O_3$	·129	—·051	·078	—·078	----
$[Fe,Mn,Mg]O$	·481	----	·481	—·078	·403
CaO	·209	----	·209	—·078	·181
$[K,Na]_2O$	·050	----	·050		
H_2O	·030	—·051			Total RO = ·584
F_2	·021				

Proportion of radicals and remaining bases:—

	Ratios	Per cents
$[Al_2O(F,OH)_2]''O$	·051	7·1
$[Al_2O_4RNa_3]''O$	·078	11·0
$[Fe,Mn,Mg]O$	·403	56·5
CaO	·181	25·4
		100·0

According to the interpretation, in this analysis all of the fluorine and water are needed for the alumo-hydroxyl radical; sodium is not quite sufficient for the second basic radical, so a very little of its nearest related constituent, calcium, is taken; in the final residue SiO_2 and RO are present in the proportion ·588: 584 or 1 : ·992; while again it is found that the residual calcium satisfies 25 per cent of the hydrogen atoms of the amphibole acid.

ANALYSIS IX, CORNWALL, N. Y.—HUDSONITE.

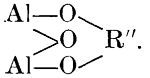
	Ratios	$\left[\begin{array}{c}\mathrm{Al{-}(F,OH)}\\ >\mathrm{O}\\ \mathrm{Al{-}(F,OH)}\end{array}\right]''$	Residue	$\left[\begin{array}{l}\mathrm{Al}{<}\begin{smallmatrix}\mathrm{O{-}Na}\\ \mathrm{O}\end{smallmatrix}\\ \qquad >\mathrm{R}\\ \mathrm{Al}{<}\begin{smallmatrix}\mathrm{O}\\ \mathrm{O{-}Na}\end{smallmatrix}\end{array}\right]''$	Residue
$[Si,Ti]O_2$	·627	—·076	·551	—·089	·462
$[Al,Fe]_2O_3$	·165	—·076	·089	—·089	----
$[Fe,Mn,Mg]O$	·376	----	·376	—·089	·287
CaO	·189	----	·189	—·089	·165
$[K,Na]_2O$	·065	----	·065		
H_2O	·072	—·076	·003		·003
F_2	·007				
					Total RO=·455

Proportion of radicals and remaining bases:

	Ratios	Per cents
$[Al_2O(F,OH)_2]''O$	·076	12·2
$[Al_2O_4RNa_2]''O$	·089	14·3
$[Fe,Mn,Mg]O$	·287	46·3
CaO	·165	26·6
H_2O	·003	·5
	·620	100·0

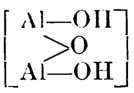
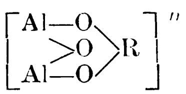
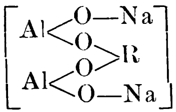
The interpretation of this analysis is essentially like that of the previous one.

Analysis X, Mte. Somma.—In this analysis the amount of water is small and only a trace of fluorine is present, consequently in order to establish a 1 : 1 ratio between SiO_2 and RO it seems necessary to assume, in addition to the radicals previously suggested, a third one of the following type :



$$\begin{array}{l}\mathrm{Al{-}O}\diagdown\\ \quad>\mathrm{O}\quad \mathrm{R}''.\\ \mathrm{Al{-}O}\diagup\end{array}$$

The interpretation is then as follows:—

	Ratios		Residue		Residue		Residue
$[Si,Ti]O_2$	·662	—·043	·619	—·032	·587	—·097	·490
$[Al,Fe]_2O_3$	·172	—·043	·129	—·032	·097	—·097	- - - -
$[Fe,Mn,Mg]O$	·450		·450	—·032	·418	—·097	·321
CaO	·214		·214		·214 }	—·097	·169
$[K,Na]_2O$	·052		·052		·052 }		
H_2O,	·042 }	—·043	——				——
F_2	·001 }					Total RO	·490

Proportion of the radicals and remaining bases :—

	Ratios	Per cents
$[Al_2O(OH)_2]''O$	·043	6·5
$[Al_2O_3R]''O$	·032	4·8
$[Al_2O_4RNa_2]''O$	·097	14·7
$[Fe,Mn,Mg]O$	·321	48·5
CaO	·169	25·5
	·662	100·0

Except for the added radical the interpretation of this analysis is like that of the previous ones, and again the residual calcium replaces 25 per cent of the hydrogen of the amphibole acid.

Attention will next be called to some varieties of hornblende which do not conform to the two groups previously considered.

XI. *Basaltic Hornblende from Bilin, Bohemia.*—To collectors, this is probably the best known of all basaltic hornblendes. It occurs in good sized and well formed crystals, generally showing the forms *m* (110), *b* (010), *r* (011) and *p* $(\bar{1}01)$, often developed so as to appear like a hexagonal prism with rhombohedral terminations. The material used for analysis was obtained from carefully selected crystals, sent to this laboratory by Mr. Warren M. Foote of Philadelphia. The material used for analysis floated on the heavy solution at the specific gravity 3·242 and sank at 3·210, the average being 3·226. The results of the analysis are as follows—

	I	II	Average	Ratios		Per cents of protoxide bases	
SiO_2	39·88	40·02	39·95	·666	·687		
TiO_2	1·70	1·66	1·68	·021			
Al_2O_3	17·49	17·68	17·58	·173	·218		
Fe_2O_3	7·25	7·25	7·25	·045			
FeO	2·18	----	2·18	·031	·694	4·5	55·5
MnO	trace	----	trace	----		----	
MgO	14·14	14·16	14·15	·354		51·0	
CaO	12·07	11·86	11·96	·213		30·7	41·1
K_2O	1·98	----	1·98	·021		3·0	
Na_2O	3·16	----	3·16	·051		7·4	
H_2O	·55	·53	·41	·023		3·3	
F_2	·03	----	·03	·001		·1	
Loss at 110°			·13				
			100·46			100·0	
		$O=F_2$	·01				
			100·45				

In this analysis it will be noted that with a large R_2O_3 quotient the ratio of SiO_2 : RO = ·687 : 694 = 1·00 : 1·01, or almost exactly 1 : 1; thus differing from analysis VII to X (summarized on page 42), all of which showed an excess of RO. It is also interesting to note that the ratio of this hornblende is like that of garnet; SiO_2 : R_2O_3 : RO being 3·00 : 0·95 : 3·03, a very close approximation to 3 : 1 : 3.

In the interpretation of the analysis there may be assumed, in addition to the alumo-hydroxyl radical, one similar to that used in analysis X, $[Al_2O_3R]$, except that in this case it is proposed to double the radical and make one R equal (Fe,Mg) the other Na_2 plus a little Ca; or, since there is practically no fluorine in the mineral, the water may be regarded as basic and only one radical need be used. The results in detail, regarding (OH) as combined with alumina, are as follows:

	Ratios	$\left[\begin{matrix}Al-OH\\ >O\\ Al-OH\end{matrix}\right]''$	Residue	$[Al_2O_3(Fe,Mg)]''$ $[Al_2O_3(Na_2,Ca)]''$	Residue
$[Si,Ti]O_2$	·687	—·024	·663	—·194	·469
$[Al,Fe]_2O_3$	·218	—·024	·194	—·194	----
$[Fe,Mg]O$	·385	----	·385	—·097	·288
CaO	·213	----	·213	—·097	·188
$[K,Na]_2O$	·072	----	·072		
H_2O	·023	—·024	----	----	----
F_2	·001				
				Total RO =	·476

Or disregarding the small amount of fluorine present and considering all the water as basic, only the second radical need be used, as follows:

	Ratios	$[Al_2O_3(Fe,Mg)]''$ $[Al_2O_3(Na_2,Ca)]''$	Residue
$[Si,Ti]O_2$	·687	—·218	·469
$[Al,Fe]_2O_3$	·218	—·218	----
$[Fe,Mg]O$	·385	—·109	·276
CaO	·213	—·109	·176
$[K,Na]_2O$	·072		----
H_2O	·023		·023
		Total RO =	·475

Proportion of radicals and remaining bases, I regarding (OH) as combined with Al, II regarding water as basic:

	Ratios I	Per cents I	Ratios II	Per cents II
$[Al_2O(OH)_2]''O$	·024	3·4	----	----
$[Al_2O_3R]''O$	·194	28·0	·218	31·5
$[Fe,Mg]O$	·288	41·5	·276	39·8
CaO	·188	27·1	·176	25·4
H_2O	----	----	·023	3·3
	·694	100·0	·692	100·0

Of the two interpretations the latter is probably the simpler and brings the residual calcium nearer to 25 per cent as in the previous analysis. It should be pointed out also that if the basic alumo-radical used in this analysis is taken by itself and combined with its equivalent of silica, the result becomes $(Na_2,Ca)(Fe,Mg)Al_4Si_2O_{12}$, analogous in type to the basic alumo-silicate molecule of Tschermak, page 24. The essential difference in this particular case between Tschermak's theory and the present one is that, according to the former a definite basic alumo-silicate molecule is regarded as isomorphous with $Ca(Fe,Mg)_3Si_4O_{12}$.

XII. *Hornblende from Grenville township, Quebec, Canada.*—This hornblende is very unusual on account of the large amounts of alumina and fluorine it contains and the low percentages of iron, a combination not often met with. It has been analyzed by Prof. B. J. Harrington,* who has kindly sent on material for study, and by R. A. A. Johnston.† The color of the mineral is a light brown, with somewhat of a reddish tone : it is unusually transparent and shows a perfect prismatic cleavage. The specific gravity as given by Harrington is 3·110. The new analysis by Stanley, from which the ratio is calculated, confirms the results of the earlier analyses.

	Harrington	Johnston	Stanley	Ratios		Per cents of protoxide bases	
SiO_2	45·50	46·09	45·79	·763	·778	56·5	57·5
TiO_2	·68	undet.	1·20	·015	·778		
Al_2O_3	12·25	12·93	11·37	·112			
Fe_2O_3	·28	·79	·42	·003	·115		
FeO	·75	none	·42	·006			
MnO	·11	·36	·39	·006	·934	·6	57·7
MgO	20·63	20·82	21·11	·528		·6	
CaO	13·31	12·91	12·71	·227		56·5	
K_2O	1·76	1·84	1·69	·018		24·3	30·5
Na_2O	2·76	2·36	2·51	·040		2·0	
H_2O	·40	·66	·67	·037		4·2	
F_2	2·80	2·84	2·76	·072		3·9	
						7·9	
	101·23	101·60	101·06				
$O=F_2$	1·17	1·19	1·16			100·0	
	100·06	100·41	99·90				

It may be noted first that with a sesquioxide quotient of ·115 the ratio of $SiO_2 : RO+F_2$ is as 1 : 1·20, which is not exactly in accord with the results obtained from analyses VII

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* This Journal, xv, 392, 1903.

† Geol. Sur. of Can., vol. xiii.

to X as summarized on page 42. The relations, moreover, are not materially altered if the titanium is regarded as Ti_2O_3, when the excess of oxygen recorded in the analysis as TiO_2 would be just about sufficient to convert the FeO and MnO of the analysis to sesquioxides: according to the latter interpretation the sesquioxide quotient becomes ·128, and the ratio of $SiO_2 : RO = 1 : 1·21$. With the high percentage of fluorine in the mineral it seems necessary to assume that some of it is united with a bivalent element, magnesium for example, to form a radical [MgF]; and according to this assumption a balance may be struck so as to leave a final residue in which $SiO_2 : RO = 1 : 1$. The interpretation is as follows:—

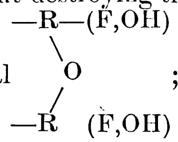
	Ratios	$\left[\begin{matrix}MgF\\MgF\end{matrix}\right]''$	Residue	$\left[\begin{matrix}Al—F\\ \quad >O\\ Al—F\end{matrix}\right]$	Residue	$\left[\begin{matrix}Al<\begin{smallmatrix}O—Na\\O\end{smallmatrix}\\ \qquad >R\\ Al<\begin{smallmatrix}O\\O—Na\end{smallmatrix}\end{matrix}\right]''$	Residue
$[Si,Ti]O_2$	·778	—·038	·740	—·034	·706	—·081	·625
$[Al,Fe]_2O_3$	·115	----	·115	—·034	·081	—·081	----
$[Fe,Mn,Mg]O$	·540	—·076	·464	----	·464	—·081	·383
CaO	·227	----	·227	----	·227	—·081	·204
$[K,Na]_2O$	·058	----	·058	----	·058		
H_2O	·037	----	·037	----	·037	----	·037
F_2	·072	—·038	·034	—·034	----	----	
						Total RO	·624

Proportion of radicals and remaining bases:—

	Ratios	Per cents
$[MgF']_2O$	·038	4·9
$[Al_2OF_2]''O$	·034	4·4
$[Al_2O_4RNa_2]''O$	·081	10·4
$[Fe,Mn,Mg]O$	·383	49·3
CaO	·204	26·2
H_2O	·037	4·8
	·777	100·0

The final result here again shows 25 per cent (a little over) of the hydrogen atoms replaced by calcium.

In analysis I there was noted a slight excess of fluorine over that required by the alumina to form the radical $[Al_2OF_2]''$, and it may be assumed that a very small amount of the radical [MgF] is present in that variety of tremolite.

Summary and Conclusion.—The chemical composition of amphibole can be explained by assuming that it is based upon a metasilicate molecule, which is, however, undoubtedly of a multiple and complex nature. The uniformity in crystallization of the different varieties in spite of the fact that they show a wide range in their chemical composition, is a strong argument for the uniformity in structure of the acid part of the molecule, enabling it to exert a controlling influence throughout the series and so to determine the crystal form. That fluorine and hydroxyl present are integral parts of the amphibole molecule and that they are to be regarded as isomorphous with the protoxides is considered as definitely proven by the results of the analyses. The presence in many amphiboles of considerable amounts of sesquioxides is explained by their introduction into the metasilicate molecule in the form of various basic, bivalent radicals. It is suggested that the character of these radicals and the degree to which they enter the amphibole molecule may be due to the influence of *mass effect* determined by the conditions under which the mineral was formed. This method of interpretation of the analyses of amphibole is upheld by the following facts: first, in the analyses of the simpler varieties, tremolite and actinolite, the 1 : 1 ratio between RO and SiO_2 is very sharp and indicates clearly that the structure of the molecule is that of a metasilicate and the small amounts of RO present cannot be introduced into the formula without destroying this ratio except in the form of the bivalent radical  ; secondly, the identity of the crystalline structure of the whole amphibole series points strongly to the assumption that the acid radical is the same throughout; thirdly, in the analyses of the hornblendes, by the assumption that two or more radicals, containing the trivalent elements with smaller amounts of the protoxide bases, enter the molecule isomorphous with RO, the residue left after the subtraction of these molecules gives the metasilicate ratio of $RO : SiO_2 = 1 : 1$; fourthly, in all cases the calcium oxide of the analyses together with the small amounts of oxides of the alkalies available forms very closely 25 per cent of the various radicals and bases, or in other words replaces one-fourth of the hydrogen atoms of the amphibole acid. This last fact is too constant throughout the analyses to be looked upon as a coincidence, but would seem rather to be a fundamental fact concerning the amphibole molecule, and furnishes one of the strongest pieces of evidence as to the correctness of the present method of interpreting the chemical constitution of the mineral.

Mineralogical Laboratory of the
Sheffield Scientific School of Yale University,
New Haven, Conn., October, 1906.